Aerodynamic performance evaluation of twinjet afterbody using flow through balance

M. Viji[1] , A. Sathia narayanan[1], N B Mathur[2]

Abstract

To understand / evaluate behaviour of these complex jets freestream interactions, experiments were carried out in the freestream Mach number range of 0.6 to 1.8 varying jet pressure ratios in the range of 1 to about 15 on a twin jet afterbody configuration. Test results show that afterbody total drag in general increased (for the Mach number range of this investigation) with the increase in jet pressure ratios due to the entrainment effect of the twin supersonic nozzle jets flow for this afterbody configuration. Oil flow visualization studies also show the intense effect of twin jets freestream interactions at transonic speeds as is indicated by large separated flow regions in and around the base region / nozzles external surface, resulting in relatively a higher transonic drag.

1. Introduction

The design and development of new military aircraft has motivated research in the aft-end problems of airframe-engine nozzle integration. Study on aft-end has become especially critical because of the requirements of multi-mission aircraft effectively at subsonic, transonic and supersonic speeds. Boundary layer separation and its associated flow phenomenon taking place around the afterbody/base region of combat aircraft in the presence of twinjet nozzle flow is quite complex [1-5]. Particularly, twin jets – freestream interactions near the aft-end of the combat aircraft can affect its afterbody drag significantly [6-8]. For example, for a twin jet combat aircraft, afterbody-nozzle drag may be as large as 20-50% of the total drag at transonic speeds [7-9]. Installation of axisymmetric nozzles in twin jet combat aircraft configuration introduces a number of flow interaction effects which needs to be minimized in order to achieve high performance aircraft design. These interactions are associated mainly with jet exhaust plume effects, afterbody contours, nozzle afterbody geometry, tail support boom, fairing design, nozzle/engine spacing etc.[5-9].

To understand / evaluate behaviour of these complex jets freestream interactions, a hardware system has been developed for the tests in base flow wind tunnel [10-12]. The unique features of the base flow wind tunnel are effectively utilized [13-16] and afterbody total drag is measured directly in the presence of twin jet nozzle exhausts for the afterbody configuration (Fig.1) having elliptic cross section (a=63.5mm, b=45mm, L/dm = 1, β = 12º, s/dn = 1.21, Mj = 1.8), relevant to twin jet combat aircraft configurations. Afterbody drag in the presence of twin jet nozzle exhausts is measured using the direct afterbody drag measurement technique developed and validated earlier at NAL [17-22]. This measurement system developed, patented [20] may be very useful for the aerospace development programmes where it is generally required rapidly to assess the effects on afterbody / base drag of various design features such as afterbody / boat-tail geometry, tail support boom interference, tail surface geometry, nozzle / engine spacing etc.

To understand / evaluate behaviour of these complex jets freestream interactions, experiments were carried out in the freestream Mach number range of 0.6 to 1.8 varying jet pressure ratios in the range of 1 to about 15 on a twin jet afterbody configuration. Test results show that afterbody total drag in general increased (for the Mach number range of this investigation) with the increase in jet pressure ratios due to the entrainment effect of the twin supersonic nozzle jets flow for this afterbody configuration. Oil flow visualization studies also show the intense effect of twin jets freestream interactions at transonic speeds as is indicated by large

[1] Scientist, *Experimental Aerodynamics Division, CSIR-NAL, Bangalore, India* ,vijim@nal.res.in
[2] Emeritus Scientist, CSIR, *Experimental Aerodynamics Division, CSIR-NAL, Bangalore, India,*

separated flow regions in and around the base region / nozzles external surface, resulting in relatively a higher transonic drag.

II. Description of test facility

The 0.5m diameter base flow wind tunnel [10-12] is a special purpose blow down type tunnel operated using NAL 10.5 kg/cms^2 high pressure system. The special feature of this tunnel is the axisymmetric variable geometry supersonic nozzle, which can provide test Mach numbers in the range of 0.5 to 3.5 (Unit Reynolds number in the range of 10-50 Million/m). The annular nozzle has inner and outer diameter of 127mm and 381mm respectively at the exit. The models are supported by nozzle inner body and therefore, the support interference is eliminated [11, 12]. Different supersonic freestream Mach numbers in this tunnel are obtained by positioning the nozzle outer body at different stream wise locations with reference to the fixed inner body [11, 12]. Axisymmetric afterbody-nozzle models of 127mm maximum diameter can be tested without or with clod jet(s). There is a provision and separate control in this tunnel for the supply of high pressure air required for jet simulation of the afterbody-nozzle flow of aerospace vehicles.

Advantages of this tunnel as compared to conventional test facilities are:

- Avoids support interference, an essential feature desirable for afterbody/base flow studies.
- Test Mach numbers can be easily changed by variable geometry axisymmetric nozzle.
- Well-developed zero pressure gradient turbulent boundary layer characteristics on the afterbody.
- Provision to supply cold jet for the nozzle flow simulation.

III. Model details

To test this twin jet afterbody model (Fig.1) having elliptic cross section (non-axisymmetric) in this 0.5m diameter axisymmetric base flow wind tunnel, a transition section of length 100mm is designed to provide transformation of circular section (dm=127mm dia) to elliptic cross section (127mm x 90mm). Ratio of twin jet afterbody model length to diameter (L/d_m) is 1, relevant to combat aircraft configuration. Throat diameter of twin jet nozzles are 25mm and are designed to provide jet Mach number of 1.8. The ratio of jet exit diameter (dj) to the jet nozzle external diameter (dn) i.e (dj/dn) is 0.6. Separation distance (s) between the nozzles is 60mm and ratio of this separation distance to the nozzle external diameter (s/dn) is equal to 1.21, relevant to combat aircraft configurations (Refs.6,8). Surface geometry of the model has been designed using CATIAV5 and solid works.

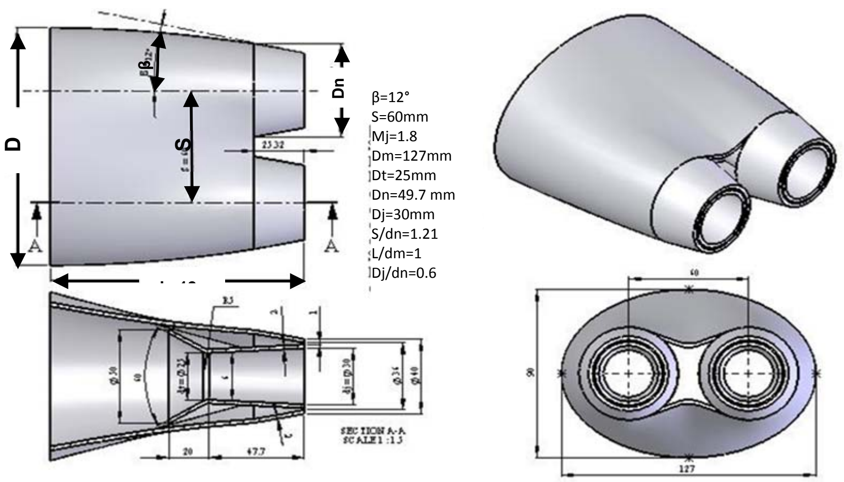

Fig.1 Geometric details of twin jet afterbody –nozzle model relevant to combat aircraft configurations

IV. Instrumentation

Afterbody-nozzle drag was measured using a calibrated annular 3-component strain gauge balance [15,19-21] of axial force capacity of 80 kgf. For the present investigations, the strain gauge balance was used mainly for the measurement of the axial force under various operating conditions of the nozzle. The normal force and the pitching moments were negligible for the afterbody models which were kept essentially at zero angle of the attack for these test conditions.

Static pressure in the model 'cavity' and 'split seal' regions were measured using a 15psid (103.4 KN/m^2) ESP scanner ; the pressures were measured with the reference tube of the scanner connected to the ambient pressure. Tunnel freestream stagnation and static pressures were measured using Druck pressure transducers of the range of 150psi (0-1034 KN/m^2) and 25psid ($\pm$ 172.37 KN/m^2) respectively. All pressure sensors were calibrated using Druck pressure calibrator (Model DPI 603).

V. Afterbody Drag measurements and Data reduction

The afterbody drag is determined from the axial force measured by the strain gauge balance, corrected for the model 'cavity' and 'split seal' pressures, and non-dimensional using the reference cross-sectional area and freestream dynamic pressure. In order to obtain seal and cavity pressure drag values, four tapings at four equally spaced circumferential locations and four static pressure tapping at four locations along the length of the cavity were provided.

Thus

$$D_{AB}=F_{bal}-(p_s-p_\infty)\,A_s-(p_s-p_\infty)\,A_c$$

Where,

F_{bal} = Axial force measured by the balance
A_s = Annular cross-section area of the seal location
A_c = Cross-sectional area of the model cavity
A_{ref} = Cross-sectional area of the twin jet afterbody model
p_s = Static pressure measured at the seal location
p_c = Static pressure in the model cavity
p_∞ = Freestream static pressure
q_∞ = Freestream dynamic pressure
C_{DAB} = Afterbody total drag coefficient

Thus,

$$C_{DAB} = D_{AB} /(q_\infty * A_{ref})$$

VI. Results

Aerodynamic performance of this twin jet afterbody-nozzle configuration is evaluated through the study of the effect of freestream Mach number (M_∞) and jet pressure ratios (P_{oj}/p_∞) on the afterbody total drag and base drag characteristics. Jet pressure ratios were varied in the freestream Mach number range of this investigation to simulate nozzle jet exhaust, relevant to nozzle operating conditions of twin jet combat aircraft configurations.

Jet-off drag characteristic

Figs.2a,b show the variation of afterbody total drag and base drag (without jets) respectively with the freestream Mach number range of this twin jet afterbody configuration. As seen, there is a sharp increase in afterbody total drag in transonic freestream Mach number range (M_∞ = 0.9 to 1.2); maximum at M_∞=1.2.

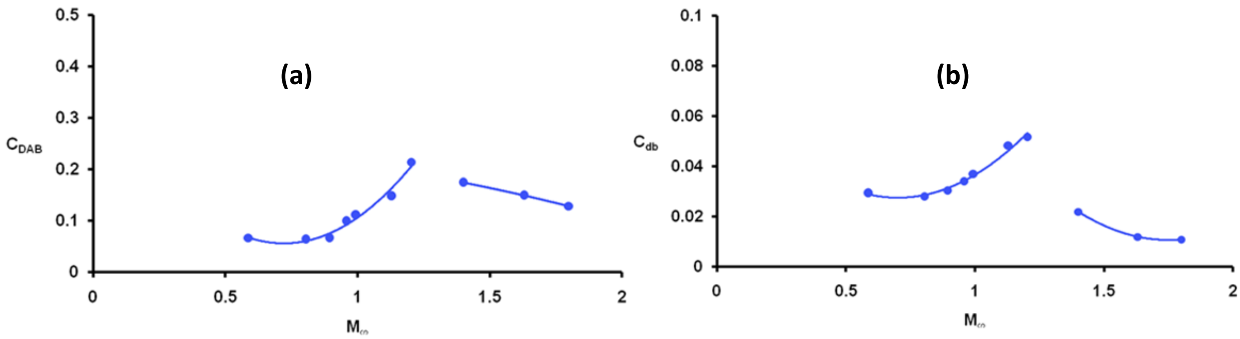

Fig 2. (a) Afterbody total drag (b) base drag characteristics of twin jet afterbody model (jet-off)

Afterbody total drag decreased in the supersonic freestream Mach number range (M_∞=1.4-1.8) of this investigation. Similar trend is seen (Fig.2b) for the base drag variation with freestream Mach numbers. Test results also show (Figs.2a,b) that the base drag contributes about 20-30% of the afterbody total drag at subsonic / transonic freestream Mach number while it contributes about 10-20% of the afterbody total drag at supersonic freestream Mach numbers (M_∞=1.4-1.8).

Effect of jet pressure ratio

Variation of afterbody total drag and base drag characteristics are as given in the figs 3a,b for the typical freestream Mach numbers of 0.80, 0.95, 1.2 and 1.6 respectively, varying jet pressure ratios (P_{oj} / p_∞) in the range from 1 (jet-off) to about 15. As seen (Figs.3a,b), afterbody total drag at subsonic, higher transonic and supersonic freestream Mach numbers increased with the increase in jet pressure ratios due to the predominant entrainment effect of the twin supersonic nozzles jets for this afterbody configuration. At transonic freestream Mach number (M_∞=0.95, Fig.3), afterbody total drag as well as base drag increased with the increase in jet pressure ratios upto 6 (due to the over expanded (separated) jets freestream interactions at low jet pressure ratios; P_{oj} / p_∞ < 6).

It can also be seen for this afterbody configuration (Fig.1) where the twin jet nozzles exhaust plane is downstream of the main body and base plane region, the effect of jets-freestream interaction is seen to be predominant in and around the base region / rear end of nozzles

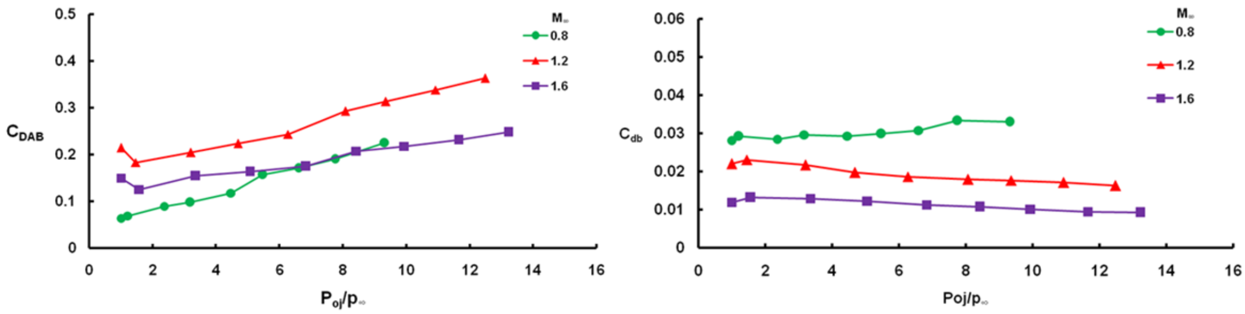

Fig.3 Comparison of (a) afterbody total drag and (b) base drag characteristics of twin jet afterbody model at subsonic, transonic and supersonic speeds

external surface (Fig.3). Test results at higher transonic (M_∞ =1.2) and supersonic freestream Mach numbers show (Fig.3) that though the afterbody total drag increased with the increase in jet pressure ratios, the base drag continuously decreased with the increase in jet pressure ratios (beyond P_{oj} /p_∞ =2). This seems to be due to the favourable effects of twin jets-freestream interactions (particularly in and around the base region) with the increase in jet pressure ratios resulting in the decrease in base drag (Fig.3) due to the increase in jet plume displacement effects (with the increase in twin jet nozzles pressure ratios).

Afterbody total drag / base drag characteristics of twin jet afterbody configuration

Fig.3 show the comparison of afterbody total drag and base drag characteristics of this twin jet afterbody configuration at the typical subsonic, transonic and supersonic speeds M_∞ =0.8, 1.2 and 1.6. These test results (Fig.3) clearly show the behaviour of twin jets-freestream interactions causing changes in afterbody total drag / base drag for the freestream Mach number range of this investigation. As seen (Fig.3), afterbody total drag in general increased with the increase in jet pressure ratios at the subsonic, transonic as well as supersonic speeds. However, there is a sharp increase in afterbody total drag at subsonic freestream Mach number (as compared to that at transonic and supersonic freestream Mach number due to the predominant entrainment effect of twin supersonic nozzles jets (M_j = 1.8) at subsonic freestream Mach number (M_∞ =0.80). Also as seen (Fig.3b), base drag at M_∞ = 0.80 remained higher than that at M_∞=1.2 & 1.6 due to the predominant entrainment effect of twin supersonic nozzles jets (M_j = 1.8) at subsonic freestream Mach number (M_∞ = 0.80). Also, as seen at subsonic speeds, there is no significant effect of jet pressure ratios on base drag due to the interaction of separated jets flow (over-expanded jets for P_{oj} /p_∞ < 6) with the separated freestream flow at the base region. However at higher freestream Mach numbers (M_∞ > 1.2), there is a trend of decrease in base drag with the increase in jet pressure ratios due to the increase in jet plume displacement effects of twin jets with the increase in jet pressure ratios.

Effect of Mach number: Behavior of twin jets-freestream interactions at a given jet pressure ratio

To understand behaviour of twin jets-freestream interactions on the afterbody total drag characteristics for the different operating conditions of the twin jet nozzles, the afterbody total drag data (Fig.4) at P_{oj} /p_∞ =6 (for the entire freestream Mach number range) is compared with that at jet-off condition (i.e. P_{oj} /p_∞ =1). P_{oj} /p_∞ =6 represents here the fully developed conditions of the jet nozzles flow for M_j = 1.8.

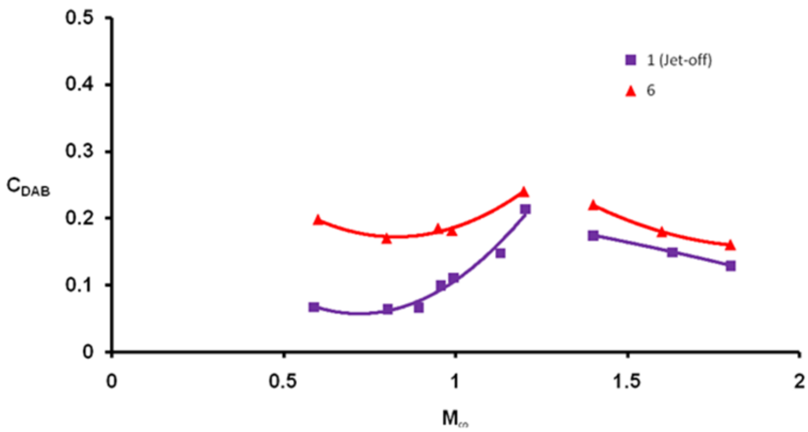

Fig.4 Afterbody total drag characteristics of twin jet afterbody configuration: Comparison of effects of twin jets-freestream interactions at fully developed conditions of the jet nozzles flow

Test results show (Fig.4) that there is a large increase in afterbody total drag for the jet-on condition (P_{oj} /p_∞ =6) with respect to afterbody total drag at the jet-off condition for the subsonic freestream Mach numbers (M_∞ ≤ 0.9) when compared to afterbody total drag at transonic and supersonic freestream Mach numbers. This is mainly due to the predominant entrainment effect of twin supersonic jets at subsonic freestream Mach numbers (due to the large difference in velocities between the supersonic jet flows (M_j = 1.8) and subsonic freestream Mach numbers) and the lower entrainment effect of supersonic jets at transonic / supersonic freestream Mach numbers.

Also, as the freestream Mach numbers increased (Fig.4) through transonic to supersonic Mach numbers range (at $P_{oj} /p_\infty = 6$), the differences in the velocities between the supersonic jets and transonic / supersonic freestream Mach numbers decreased, causing a lower intensity of entrainment effect of twin jets, thus resulting in the lower differences in the afterbody total drag values at the jet-on (P_{oj} /p_∞ =6) and corresponding jet-off (P_{oj} /p_∞ =1) conditions (Fig.4).

Oil flow visualization studies

Oil flow visualization studies were carried out at typical freestream Mach numbers of 0.80, 0.95, 1.2 and 1.6 to understand broad flow features of this twinjet afterbody system relevant to twinjet combat aircraft configuration.

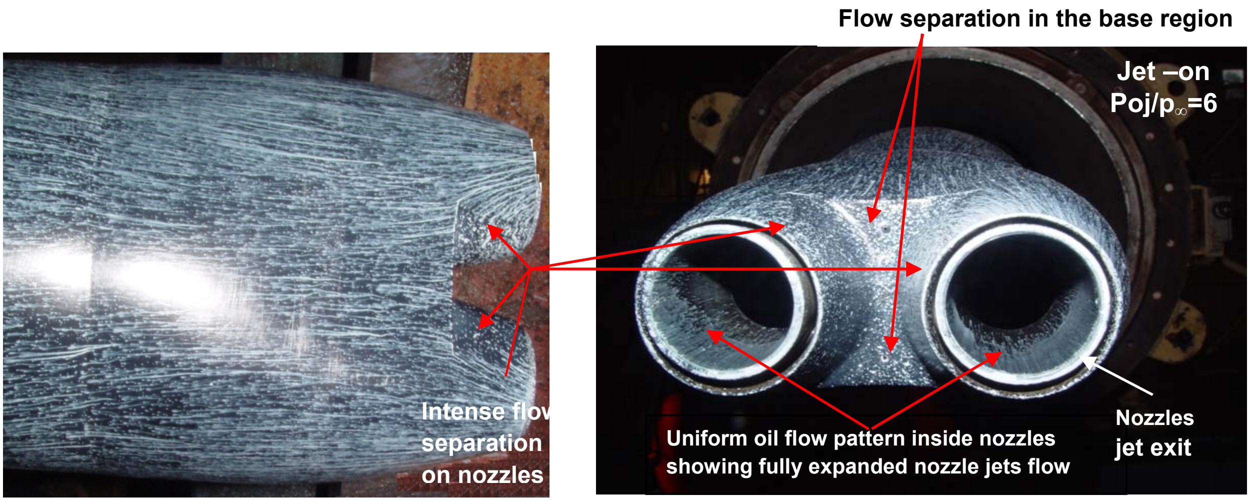

Fig.5 Oil flow pattern showing the effect of twin jets – freestream interactions at transonic speeds

As seen from the oil flow patterns (Fig.5), the flow over the main part of the twin jet afterbody is uniform and attached except in and around the base region / rear end (about 20-30% of the afterbody total length). Oil flow visualization studies at transonic speeds (Fig.5) clearly show the intense effect of twin jets-freestream interactions as is indicated by the large separated flow regions (Fig.5) in and around the base region and twin jet nozzles external surface (upstream of the nozzles exit plane), resulting in relatively a higher transonic afterbody total drag (Fig.3).

VII. Conclusions

- A test technique / technology has been developed for the direct measurement of afterbody drag in the presence of twinjet nozzle exhausts relevant to combat aircraft configurations.
- Test results show that afterbody total drag in general increased (for the Mach number range of this investigation) with the increase in jet pressure ratios due to the predominant entrainment effect of the twin supersonic nozzle jets for this afterbody configuration
- Oil flow visualization studies clearly show the intense effect of twin jets-freestream interactions at transonic speeds as is indicated by the large separated flow regions in

and around the base region / nozzles external surface, resulting in relatively a higher transonic afterbody drag.

- This measurement system / test technique developed may be very useful for the current aerospace development programmes, particularly for the twinjet MCA configuration being developed in the country.

Acknowledgments

The author wishes to thank Aeronautical Research and Development Board, India, for funding the project. The technical support of Mr.Ravi dodamani during the model design and fabrication and of Mr.Narayana swamy and Mr.Biju of base flow facility at NAL during the test campaign is gratefully acknowledged.

References

[1]Delery J and Sirieix M, "Base Flow behind Missiles", ONERA TP No. 1979-14E, 1979.
[2]Mathur N B and Yajnik K S, "Underexpended Jet-freestream Interactions on an Axisymmetric Afterbody Configuration", AIAA Journal Vol. 28, No.1, Jan. 1990.
[3]Gamal H, Moustafa. "Interaction of of Axisymmetric Twin Jets", AIAA Journal, Vol.33, No.5, 1995, pp 871-875.
[4]Bare E.A; Berrier B.L "Investigation of Installation Effects on Twin-engine Convergent-Divergent Nozzles", NASA TP 2205, Nov. 1983.
[5]Berrier B.L, Wood Jr. F.H; "Effect of Jet Velocity and Axial Location of Nozzle Exit on the Performance of a Twin-Jet Afterbody model at Mach number upto 2.2" NASA TND-5393, Sept.1969.
[6]Martens E R, "F-15 Nozzle / Afterbody Integration", J. Aircraft, Vol13, No.5, May 1976, pp 327-333.
[7]Runckel, J F, "Interference Between Exhaust System and Afterbody of Twin-Engine Fuselage Configurations", NASA TND – 7525, May 1974.
[8]Glasgow E R, "Integrated Airframe-Nozzle Performance for Designing Twin-Engine Fighters", AIAA Paper no.73-1303, Nov. 1973.
[9]Henderson W P and Berrier B L, "Airframe / Propulsion Integration Characteristics at Transonic Speeds", NASA CP 3020, April 1988.
[10]Mathur N B, Krishnan V, Ramesh G., "Calibration Studies in the Base Flow Wind Tunnel", Proc. Of National Conference on Aerodynamics, Bangalore [1998] also PD EA 9804, 1998.
[11]Mathur N B, Ramesh G, Narayan G., "Investigations in the Axisymmetric Base Flow Wind Tunnel", NAL DLR workshop on Experimental Fluid Mechanics and Turbo Machinery, NAL Bangalore Jan. 2000.
[12]Mathur N B, Ramesh G, Verma R S, Ramesh R, "Experiemtnal Studies in the 0.5m Special Purpose tunnel", Proceedings, International Symposium on Recent Advances in Experimental Fluid Mechanics, IIT Kanpur, Dec. 2000.
[13]Mathur N B, Verma R S, Ramesh R, "Development of Test Technique for the Direct Measurement of Afterbody Drag in the Presence of Jet Exhaust in the Base Flow Wind Tunnel", NAL PD EA 9801, 1998.
[14]Mathur N B, Ramesh G., "Afterbody-nozzle Drag Characteristics of LCA-GE Configuration for Three Operating Conditions of the Nozzle", NAL PD EA 0017, Sept. 2000.
[15]Mathur N B., Ahmed S, "A test technique for the Measurement of Intake Drag of Air-breathing Vehicles", Proceedings. International Symposium on Recent Advances in Experimental Fluid Mechanics, IIT Kanpur, Dec. 2000.
[16]Viswanath P R, Mathur N B, Verma R S, Ramesh R, "Semi Empirical Rear end Study : Wind Tunnel Measurements", NAL SP 0004, 2000

[17]Mathur N B , Viswanath P R, “Parametric Evaluation of Drag Characteristics of Square Base Afterbodies with Jet Flow”, NAL PD EA 0105, 2001.
[18]Mathur N B , Viswanath P R, “Drag Reduction from Square Base Afterbody at High Speeds”, Journal of Aircraft, Vol. 41, No.4, July-Aug. 2004. Also, Proceedings, 9th ACFM, Isfahan, Iran, May 2002
[19]Mathur N B , Rajeev Kumar, “A Novel Technique for the Direct Measurement of Afterobdy Drag in the Presence of Multi Jet Nozzle Exhaust”, Proceedings 16th International Symposium on Air Breathing Engines, ISABE 2003-1196, Cleveland Ohio, USA, Sept. 2003.
[20]Mathur NB , Verma RS, Ramesh R, “A Device for Measuring Aerodynamic Loads on Afterbody of Aerospace Vehicles”,
Patent : IN230950, February 28, 2009.
[21]Mathur N B , Viswanath P R, “Base Drag Characteristics of Complex Launch Vehicle Systems and its Reduction in Supersonic Flow”, NAL PD EA 0606, May 2006.